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Technologies to recover exhaust heat from internal combustion engines

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ABSTRACT

The focus of this study is to review the latest developments and technologies on waste heat recovery of exhaust gas from internal combustion engines (*ICE*). These include thermoelectric generators (*TEG*), organic Rankine cycle (*ORC*), six-stroke cycle *IC* engine and new developments on turbocharger technology. Furthermore, the study looked into the potential energy savings and performances of those technologies. The current worldwide trend of increasing energy demand in transportation sector are one of the many segments that is responsible for the growing share of fossil fuel usage and indirectly contribute to the release of harmful greenhouse gas (*GHG*) emissions. It is hoped that with the latest findings on exhaust heat recovery to increase the efficiency of *ICEs*, world energy demand on the depleting fossil fuel reserves would be reduced and hence the impact of global warming due to the *GHG* emissions would fade away.

Contents

Abbreviations: *A/R*, Aspect ratio; *B*, Biodiesel; *BASIC*, Beginner's all-purpose symbolic instruction code; BiTe, Bismuth telluride; *BPV*, Bypass valve; *BTDC*, Before top dead center; CeFeSb, Skutterudite; *CHRA*, Center housing and rotating assembly; *CI*, Compression ignition; CO, Carbon monoxide; *DF*, Diesel fuel; *DI*, Direct injection; *EGR*, Exhaust gas recirculation; *GDP*, Gross domestic product; *GHG*, Greenhouse gas; *HCCI*, Homogenous charge compression ignition; *HCPC*, Homogenous charge progressive combustion; *HEV*, Hybrid electric vehicle; *ICE*, Internal combustion engine; *ISFC*, Indicated specific fuel consumption; *K*, Total thermal conductivity; *MEP*, Mean effective pressure; *MPPT*, Maximum power point tracker; *NA*, Naturally aspirated; NO, Nitric oxide; NO_x, Nitrogen oxide; *ORC*, Organic Rankine cycle; *PV*, Photovoltaic; *PVG*, Photovoltaic generator; ρ, Electrical resistance; *S*, Thermo power; *SI*, Spark ignition; *Sin*, Sustainability index; SiGe, Silicon germanium; SnTe, Tin telluride; *T*, Absolute temperature; *TEG*, Thermoelectric generator; *TU*, Turbocharged; *VGT*, Variable geometry turbocharger; *VNT*, Variable nozzle turbocharger; *WEDACS*, Waste energy driven air conditioning system; *WHR*, Waste heat recovery; *Z*, Figure of merit; ZnBe, Zinc-beryllium; ψ, Exergy efficiency

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1. Introduction

In recent years the scientific and public awareness on environmental and energy issues has brought in major interests to the research of advanced technologies particularly in highly efficient internal combustion engines. The number of vehicles (passenger and commercial vehicles) produced from 2005 to 2010 shows an overall increasing trend from year to year despite major global economic downturn in the 2008–2010 periods (Fig. 1). Note that China's energy consumption in transportation sector is the lowest (13.5%) [1] although the country produced the highest number of vehicles in 2009 to 2010 as compared to the other countries (Table 1).

Viewing from the socio-economic perspective, as the level of energy consumption is directly proportional to the economic development and total number of population in a country, the growing rate of population in the world today indicates that the energy demand is likely to increase. It is also expected that the average increase in population growth between 2010 and 2020 is projected to be 10.74% [3–5]. For instance, the current population of Malaysia is expected to rise from 28 million in 2010 [6] to 33 million by the year 2020 [7]. In consequence, Malaysia Gross Domestic Product (*GDP*) saw a stable increase from RM 87,280 million in 1980 to RM 675,825 million in 2009 [8]. From 1980 to 2009, the per capita income also recorded an increase from RM 6341 to RM 24,604 (US$1 = RM 3.50) [8]. The energy demand of Malaysia is thus presented in Fig. 2 [9] showing a stable percentage values for transportation sector in 2002 period. As discussed before, the growing number of population puts transportation sector in a very crucial role due to its dependability towards the continuous and rapid development of a nation urban areas and the standard of living for its people. For instance, in

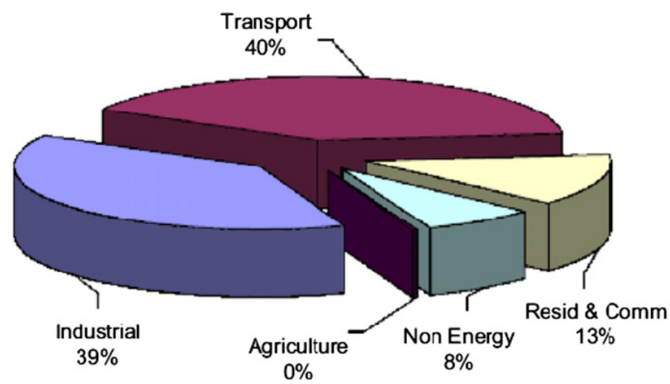

Fig. 2. Final energy usage by the main sector of Malaysia in 2002 [9].

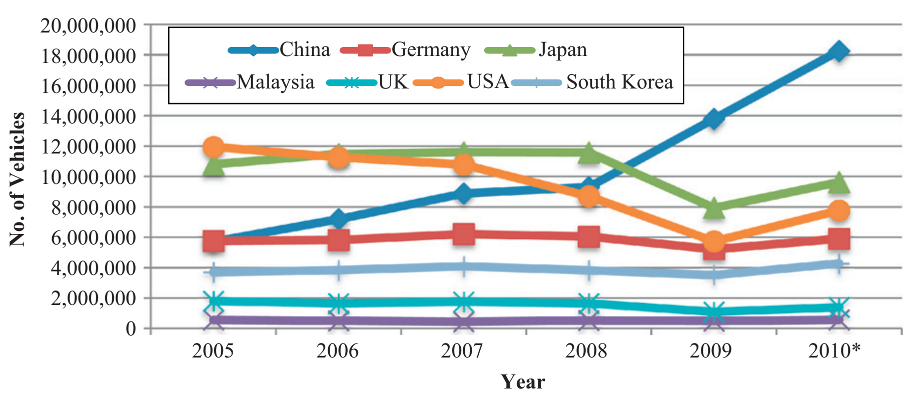

Fig. 1. Production of vehicles from 2005 to 2010 for selected countries [1,2].

Table 1
Terminal energy consumption structure by region and sector (unit: mtoe) [1].

Regions	Total consumption	Energy consumption by sector			
		Industry	Transportation	Agricultural/ commerce/civil	Non-energy use
China	597	327 (54.8)[a]	80.5 (13.5)	165 (27.6)	24.5 (4.1)
USA	1597	394 (25.3)	623 (40.0)	475 (30.5)	65.4 (4.2)
EU (15)	1057	320 (30.3)	321 (30.4)	386 (36.5)	30.2 (2.8)
Japan	359	135 (37.6)	94.4 (26.3)	119 (33.2)	10.5 (2.9)
OECD	3692	1106 (30.0)	1242 (33.6)	1120 (33.0)	125 (3.4)
Total in the world	6212	2144 (34.5)	1831 (29.5)	2035 (32.8)	201 (3.2)

[a] Percentage value inside the parenthesis.

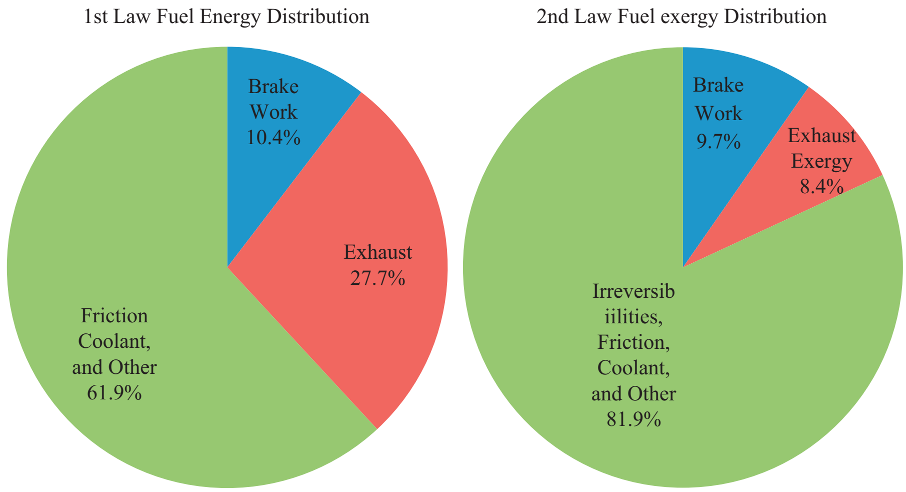

Fig. 3. 1st law and 2nd law energy and exergy distribution in an internal combustion engine [21].

2002, the transportation sector of Malaysia used about 40% of the total energy consumed as shown in Fig. 2.

A number of irreversible processes in the engine limit its capability to achieve a highly balanced efficiency. The rapid expansion of gases inside the cylinder produces high temperature differences, turbulent fluid motions and large heat transfers from the fluid to the piston crown and cylinder walls. These rapid successions of events happening in the cylinder create expanding exhaust gases with pressures that exceed the atmospheric level, and they must be released while the gases are still expanding to prepare the cylinder for the following processes. By doing so, the heated gases produced from the combustion process can be easily channeled through the exhaust valve and manifold. The large amount of energy from the stream of exhausted gases could potentially be used for waste heat energy recovery to increase the work output of the engine [10].

Consequently, higher efficiency, lower fuel consumption by improving fuel economy, producing fewer emissions from the exhaust, and reducing noise pollutions have been imposed as standards in some countries [11,12]. Hatazawa et al. [13], Stabler [14], Taylor [15], Yu and Chau [16] and Yang [17] stated that the waste heat produced from thermal combustion process generated by gasoline engine could get as high as 30–40% which is lost to the environment through an exhaust pipe. In addition, 12–25% of the available energy in a fuel will be used to drive the wheels and other accessories which technical descriptions of those literatures are heavily discussed in Refs. [14,15,18–20].

In internal combustion engines a huge amount of energy is lost in the form of heat through the exhaust gas. Conklin and Szybist [21] investigated that the percentage of fuel energy converted to useful work only 10.4% and also found the thermal energy lost through exhaust gas about 27.7%. The second law (i.e., exergy) analysis of fuel has been shown that fuel energy is converted to the brake power about 9.7% and the exhaust about 8.4% as shown in Fig. 3. In another research [22] the value of exhaust gases mentioned to be 18.6% of total combustion energy. It is also found that by installing heat exchanger to recover exhaust energy of the engine could be saved up to 34% of fuel saving [23].

2. Thermoelectric energy conversion technology

2.1. Background of thermoelectric generator

Being one of the promising new devices for an automotive waste heat recovery, thermoelectric generators (*TEG*) will become one of the most important and outstanding devices in the future. Within the recent years, the revival of interests into clean energy production has brought *TEG* technology into the attention of many scientists and engineers. Mori et al. [24] studied the potentials of thermoelectric technology in regards to fuel economy of vehicles by implementing thermoelectric (*TE*) materials available in the market and certain industrial techniques on a 2.0 l gasoline powered vehicle. Hussain et al. [25] studied the effects of thermoelectric waste heat recovery for hybrid vehicles. Stobart and Milner [26] explored the possibility of thermoelectric regeneration in vehicles in which they found out that the 1.3 kW output of the *TE* device could potentially replace the alternator of a small passenger vehicle. Stobart et al. [27] reviewed the potentials in fuel saving of thermoelectric devices for vehicles. They concluded that up to 4.7% of fuel economy efficiency could be achieved. From these articles, the understanding of *TEG* technology has been comprehensively discussed as a promising new technology to recover waste heat from internal combustion engines. Studies on thermoelectric devices are still an ongoing matter.

TE devices may potentially produce twice the efficiency as compared to other technologies in the current market [28]. *TEG* is used to convert thermal energy from different temperature gradients existing between hot and cold ends of a semiconductor into electric energy as shown in Fig. 4. This phenomenon was discovered by Thomas Johann Seebeck in 1821 and called the "Seebeckeffect". The device offers the conversion of thermal energy into electric current in a simple and reliable way. Advantages of *TEG* include free maintenance, silent operation, high reliability and involving no moving and complex mechanical parts as compared to Rankine cycle system [29] which will be discussed in the next section of this study. In regards with the applicability of *TEG* in modern engines, the ability of *ICE*s to convert fuel into useful power can be increased through the utilization of the mentioned device. By converting the waste heat into electricity, engine performance, efficiency, reliability, and design flexibility could be improved significantly. The fuel efficiency of gasoline powered, diesel and hybrid electric vehicles (*HEV*s) that utilize the power generation of *IC* engine is as low as 25% and conversely as much as 40% of fuel energy can be lost in the form of waste heat through an exhaust pipe [30]. An increase of 20% of fuel efficiency can be easily achieved by converting about 10% of the waste heat into electricity [17,31]. Furthermore, secondary loads from the engine drive trains can be eliminated with the help of *TEG* system, and as a result torque and

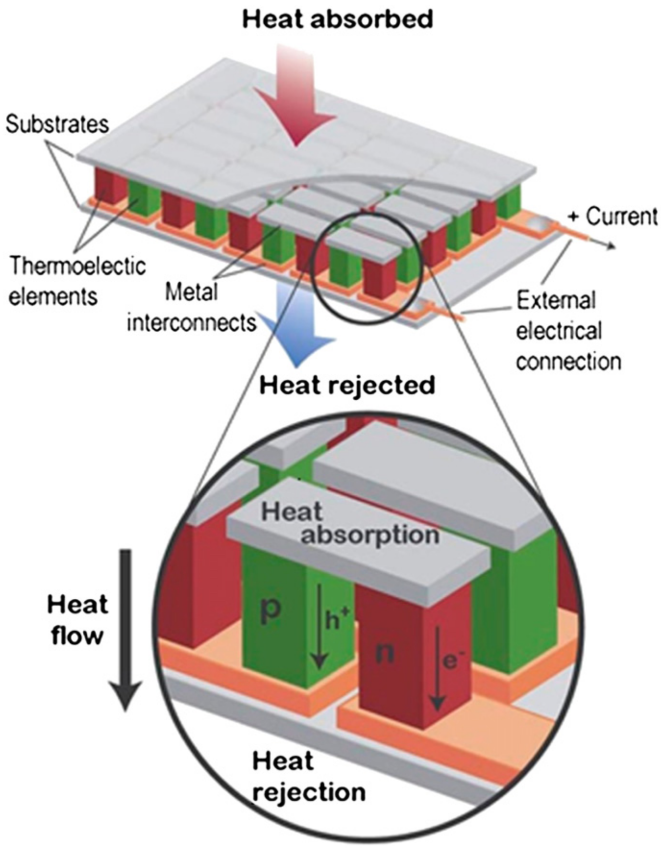

Fig. 4. Schematic of a typical thermoelectric device [32,33,67].

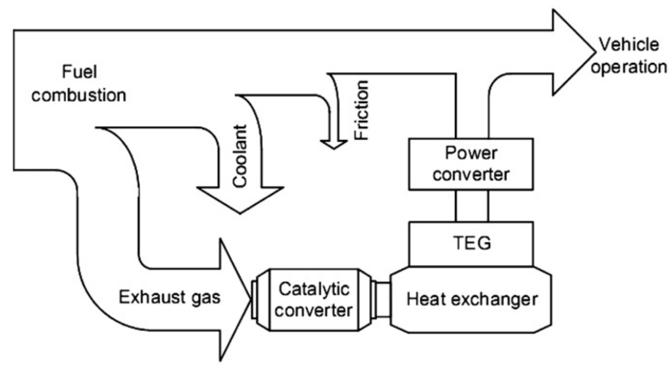

Fig. 5. A typical waste heat energy recovery system [16].

horsepower losses from the engine can be reduced. This would help to reduce engine weight and direct the most of the increased power to the drive shaft, which would in turn help to improve the performance and fuel economy. Additionally, the possibility of minimizing the battery needs and exhaustion of vehicle battery life while permitting operation of specific accessories during engine off can be achieved by utilizing *TEG* [17].

2.2. TEG in the automotive industry

For an automobile engine, there are two main exhaust heat gas sources which are readily available. The radiator and exhaust gas systems are the main heat output of an *IC* engine [34]. The radiator system is used to pump the coolant through the chambers in the heat engine block to avoid overheating and seizure [30]. Conversely, the exhaust gas system of an *IC* engine is used to discharge the expanded exhaust gas through the exhaust manifold. Zhang and Chau [30] reported that presently *TEG* is mostly installed in the exhaust gas system (exhaust manifold) due to its simplicity and low influence on the operation of the engine. Furthermore, *TEG* system including the heat exchanger is commonly installed in the exhaust manifold suitable for its high temperature region [17]. Basically, a practical automotive waste heat energy recovery system consists of an exhaust gas system, a heat exchanger, a *TEG* system, a power conditioning system, and a battery pack as shown in Fig. 5; with the operation of the *TEG* waste heat recovery system described as follows [16]:

i) During the normal operation of an internal combustion engine, the produced waste heat released through the exhaust manifold is captured by the heat exchanger mounted on the catalytic converter of the exhaust gas system.
ii) Electricity is then generated from the thermal energy captured by the heat exchanger after it is transferred to the *TEG* system.
iii) Power conditioning is performed by the power converter to achieve maximum power transfer.

2.3. Challenges of TEG

The primary challenge of using *TEG* is its low thermal efficiency (typically $\eta\text{th} < 4\%$) [35]. Thermoelectric materials efficiency depends on the thermoelectric figure of merit, *Z*; a material constant proportional to the efficiency of a thermoelectric couple made with the material. Karri et al. [36] stated that future thermoelectric materials show the promise of reaching significantly higher values of the thermoelectric figure of merit, *Z*, and thus higher efficiencies and power densities can be obtained. Materials such as BiTe (bismuth telluride), CeFeSb (skutterudite), ZnBe (zinc–beryllium), SiGe (silicon–germanium), SnTe (tin telluride) and new nano-crystalline or nano-wire thermoelectric materials are currently in development stage to improve the conversion efficiency of *TEG*s [37]. BiTe-based bulk thermoelectric material is mostly used in waste heat recovery power generation due to its availability in the market and high applicability in low and high exhaust gas temperature range [37]. The performance of a thermoelectric material can be expressed as $ZT = S^2T/k\rho$, where *S* is the thermo power, *T* the absolute temperature, κ the total thermal conductivity, and ρ the electrical resistance [33].

Another challenge which is considerable is bigger size of the radiator and extended piping to the exhaust manifold. This problem can be mitigated by using a nanofluid in a radiator system. By using nanofluid, the size and weight of an automotive car radiator could be reduced without affecting its heat transfer performance [38–40].

2.4. Recent development of TEG in automotive industry

TEG could be coupled with various other devices to maximize its potential. Yu and Chau [16] has proposed and implemented an automotive thermoelectric waste heat recovery system by adopting a Cuk converter and a maximum power point tracker (*MPPT*) controller into its proposed system as tools for power conditioning and transfer. The other exciting development of *TEG* is the combination of thermoelectric and photovoltaic (*PV*) systems which can be called as a hybrid system. Zhang and Chau [30] proposed the *TE-PV* system coupled with *MPPT* controller to achieve maximum power output. They reported that the power improvement is recorded from 7.5% to 9.4% when the hot-side temperature of the *TEG* is heated from 100 °C to 250 °C and the irradiance of *PV* generator (*PVG*) is fixed at 1000 W/m^2.

Also, when the irradiance of the *PVG* is controlled from 200 W/m^2 to 1000 W/m^2 and the hot-side temperature of the *TEG* is fixed at 250 °C, the power improvement as much as 4.8% to 17.9% can be achieved. As a result the potential use of the system opens up many possibilities for engine efficiency.

3. Six-stroke internal combustion engine cycle

The concept of a six-stroke internal combustion engine cycle is fundamentally based on the basic four-stroke engine cycle but with two added cycles to produce higher efficiency and reduce emissions. There are many patents having been awarded for designs on six-stroke cycle engine which are discussed in Refs. [41–48]. However, very limited articles on the subject of six-stroke combustion engine cycle performances have been published. Hayasaki et al. [49] proposed a six-stroke direct injection (*DI*) dual fuel diesel engine that has second compression and combustion processes as opposed to the typical four-stroke diesel engine. They used diesel–methanol fuel which reduces nitric oxide (*NO*) and soot emissions to almost zero especially for soot emission. Furthermore, a slightly lower indicated specific fuel consumption (*ISFC*) of the six-stroke diesel engine than that of the four-stroke engine was achieved. Hence, based on these papers, it can be concluded that a six-stroke cycle engine has better thermal performance and low fuel consumption potentials.

A typical four-stroke cycle involves (1) intake stroke, (2) compression stroke, (3) combustion stroke and (4) exhaust stroke. However, in a six-stroke internal combustion engine proposed by Conklin and Szybist [21], the expanded exhaust gas from the fourth stroke is trapped and recompressed by two additional strokes. Theoretically, with the addition of a couple of power strokes, more output work can be produced without any extra fuel injected into the cylinder, thus improving fuel economy of the engine. Consequently, water is injected and the steam/exhaust mixture is expanded. By closing the exhaust valve earlier than usual, the residual gas inside the cylinder will be trapped. The injected liquid water will receive energy from the recompressed gases which causes it to expand and hence increasing the pressure inside the cylinder. Hence, more work is produced through the expansion process. However, all the multi-stroke engine cycles explained in Refs. [42–46,48] employ a complete exhaust stroke during crank angle 540–720° which produces impingement on the combustion chamber surfaces when water is injected into the cylinder. Conklin and Szybist [21] believe that an engine cycle that utilizes water injection to absorb the heat directly from the exhaust gas is more practical than using the combustion chamber surfaces as the primary heat source. By employing an ideal thermodynamics model of the additional two strokes i.e., exhaust gas recompression, water injection and expansion, Conklin and Szybist [21] found out that the net mean effective pressure of the steam expansion stroke (MEP_{stream}) can be maximized by modifying the exhaust valve closing timing during the fourth stroke. As a result, the range of calculated MEP_{stream} was found out to be 0.75–2.5 bars which show a potential increase in engine efficiency and fuel consumption as the combustion mean effective pressures ($MEP_{\text{combustion}}$) of gasoline powered IC engine are typically up to 10 bars [21].

4. Rankine bottoming cycle technique

The low-grade temperature heat from the exhaust cannot be efficiently converted to electrical power by using conventional methods as seen in industrial waste heat recovery systems. In this section, a study on converting these low-grade temperature heat sources using Rankine cycle is discussed. There are many other thermodynamic cycles proposed to generate electricity from exhaust heat. These are Kalina, supercritical Rankine, organic Rankine, trilateral flash and Goswami cycles. Interestingly, Kalina and organic Rankine cycles have been compared in many studies in the past few years. DiPippo [50] reported that even though there have been claims of up to 50% of more power output for the same input for Kalina cycles as opposed to organic Rankine cycles, data from actual operations only show a difference of about 3% in favor of Kalina cycle as compared to organic Rankine cycle under similar conditions. Vaja and Gambarotta [51] mentioned that a 12% increase in the overall efficiency with respect to the engine with no bottoming. They added Organic Rankine Cycle (*ORC*) can recover only a small fraction of the released heat by the engine trough the cooling water.

4.1. Background of the technique

Rankine bottoming cycle is a derivative of the Rankine cycle. Because of the low-grade heat sources, the efficiency of the cycle depends on the selected working fluids and operating conditions of the system. Chen et al. [52] reviewed 35 different types of working fluid under different operating conditions. It may be noted that the best working fluids with the highest efficiency cycles may not be the same for other operating conditions and different working fluids. Fig. 6 shows a configuration of a Rankine cycle system and its processes plotted in a *T-s* diagram.

A *WHR* Rankine bottoming cycle system consists of a wet, dry or isentropic fluid as the working fluid, a pump to circulate the working fluid (increase in pressure), an evaporator/boiler to

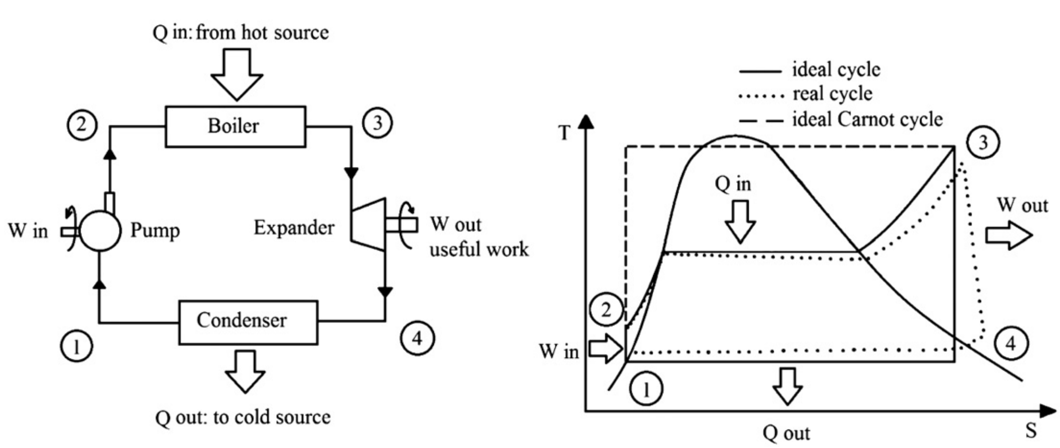

Fig. 6. Rankine cycle system [53].

absorb exhausted heat energy, an expansion machine (expander) to release power by bringing the fluid to a lower pressure level (organic vapor expands in the turbine to produce mechanical energy), a condenser to release the heat from the fluid and liquidize the fluid before starting the whole cycle again [54]. Evaporator/boiler for a Rankine cycle system is usually a heat exchanger that absorbs heat from exhaust gas that operates at a constant level of evaporating pressure [51,55].

4.2. Working fluids in Rankine cycle

Power generation by the Rankine cycle is a well adopted technology. In most applications, wet working fluid or water is used as the working fluid in the closed circuit of the cycle. Due to the thermal stability of steam (water) it can be applied in applications where the heat source temperatures are very high without the fear of thermal decomposition. However, in applications that captures heat from low-grade sources and provides output capacity smaller than 1 MW as in the case of automotive engines, organic working fluid turbines generally have higher efficiency than steam turbines due to design considerations with smaller molecular weight of working fluids and better economics [56,57]. The *T-s* diagram of working fluids can have positive slope of saturation curve, negative slope or vertical slope. Accordingly, these fluids are called wet, dry and isentropic fluids (Fig. 7).

Anorganic Rankine cycle (*ORC*) utilizes organic fluid (i.e., dry or isentropic) instead of water as the working fluid. It can be said that the efficiency of the cycle is greatly dependent on the selection of the working fluid. An organic Rankine cycle generally uses isentropic organic fluids due to their low heat of vaporization and they do not need to be superheated to increase their recovery efficiencies as needed for wet working fluid (water) [58]. Various articles have been published discussing the ideal properties and operating conditions of working fluids for a Rankine cycle. Badr et al. [59] studied properties of different organic fluids as candidates for regenerative Rankine-cycle units by using computer programs (BASIC) to predict optimal working fluid, design and operating conditions of a proposed system. Gu et al. [60] found out that the cycle efficiency of several working fluids is very sensitive to evaporating pressure but insensitive to expander inlet temperature. Hung [61] demonstrated that systems with lower irreversibility would produce a better power output. However, this would vary according to different types of working fluid and heat source. Dai et al. [62] examined the performance of an *ORC* system that utilized different working fluids. They found out that the cycles with organic working fluids produce much higher exergy efficiency than the cycle with water. In another research, He et al. [63] mentioned that one of the important characteristics of the working fluid used in *ORC* is the slope of the saturation vapor curve. They noted that efficiency is extremely affected by the evaporation temperature of the working fluid. Boretti [64,65] stated that in a given temperature gradient for optimizing the work output, the working fluid's evaporation enthalpy should be as high as possible. Furthermore, Larjola [66] stated that by using an appropriate organic fluid as a substitute for water, superlative efficiency and maximum power output can be obtained when wasted heat energy with moderate temperature is placed as the heat source at the inlet. This is due to the lower irreversibility between the working fluid and the heat source.

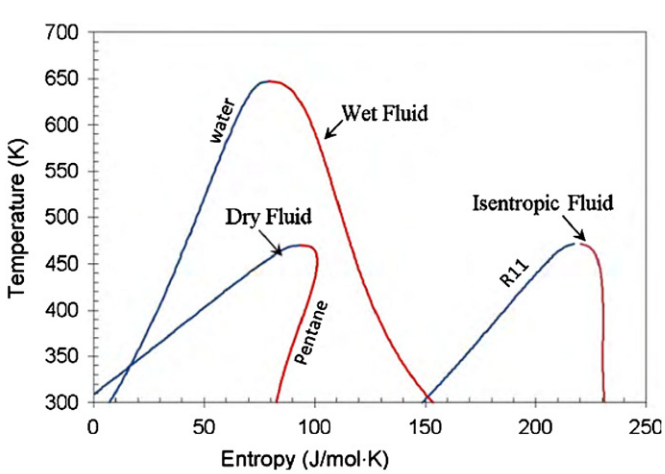

Fig. 7. Dry (e.g., isopentane), wet (e.g., water) and isentropic (e.g., R11) working fluids [52].

4.3. Considerations of working fluids

As mentioned before, working fluid has the most important role in determining the efficiency of the cycle. The selected fluid may affect various aspects of the whole system including the overall system efficiency, operating conditions, economic viability and also environmental impact due to the chemical nature of the working fluids. The selection criteria and properties of working fluids for Rankine cycle are presented in Table 2 [52]:

4.3.1. Types of working fluids

As discussed in Section 4.2, there are three types of working fluids which are dry, wet and isentropic fluids that are very much dependent on the slope of the saturation vapor curve on a *T-s* diagram (dT/ds). The type of working fluid can be determined through a simplified Equation [67]:

$$E = \frac{C_p}{T_H} - \frac{(nT_{rH}/1 - T_{rH}) + 1}{T_H^2} \Delta H_H \quad (1)$$

where $E(ds/dT)$ refers to the inverse of the slope of saturated vapor curve on *T-s* diagram, n is suggested to be 0.375 or 0.38 by [68], T_{rH} ($=T_H/T_C$) refers to reduced evaporation temperature and ΔH_H is the enthalpy of vaporization. Note that, values of E are, $E > 0$; a dry fluid, $E = 0$; an isentropic fluid and $E < 0$ for a wet fluid. Also, Chen [52] recommended that the entropy and temperature data are to be used directly if they are available to avoid large deviations due to the simplification of Eq. (1). For an organic Rankine cycle, it is strongly suggested to use isentropic or dry fluids to avoid liquid droplet impingement in the turbine blades during the expansion process.

4.3.2. Latent heat, density and specific heat of working fluids

There are different opinions on the influence of latent heats, densities and specific heats of working fluids on the Rankine cycle. One literature suggests that high latent heat and density with low specific heat liquid are preferable for its advantage of absorbing more energy from the source in the evaporator and as a result reducing pump consumption, size and the required flow rate [69]. Another literature suggested that a low latent heat fluid would provide the best operating condition due to the saturated vapor at the turbine inlet [70]. For a more complete conclusion, an analytical investigation was conducted for enthalpy change

Table 2
Specifications of the hybrid engine [53].

Engine type	Naturally aspirated
Maximum torque	95 Nm
Maximum power	54.7 kW
Minimum BSFC	235 g/(kW h)

during the turbine expansion by using the following Equation [52]:

$$\Delta h_{isentropic} = C_p T'_{in}[1 - e^{l((1/T_1)-(1/T_2)/C_P}] \quad (2)$$

where $\Delta h_{isentropic}$ refers to the unit isentropic enthalpy drop (i.e., work output) through a turbine, T'_{in} is the turbine inlet temperature, L is the latent heat of the working fluid, T_1 and T_2 are the saturation temperatures of two points on the *T-s* diagram with $T_1 > T_2$ [52]. Eq. (2) proves that the higher latent heat of a fluid could produce higher unit work output when the other parameters are known. Also, fluids with higher density would produce the same power output with smaller sized equipment. Study done in [52] reaches the same conclusion as in [69] that working fluids that have high latent heat and density with low liquid specific heat would give rise to high turbine work output.

4.4. Analysis of Rankine bottoming cycle in a vehicle

Duparchy et al. [53] have studied a Rankine bottoming cycle system implemented in a hybrid vehicle. The following discussion attempts to summarize their findings. Table 2 provides the specifications of engine they were testing with.

The operating points that were chosen based on for design and simulation at constant speeds of 70 km/h and 120 km/h that corresponds to rolling resistance of 5 kW and 20 kW, respectively are listed in Table 3. Fig. 8 shows the layout of the Rankine bottoming cycle system.

Main sources of waste energies can be found in the exhaust gases and the cooling system of a vehicle. The following discussion attempts to analyze the energy and exergy balances of these two sources.

Table 3
Operating points of parameter 1 and 2 [53].

	Operating parameter 1	Operating parameter 2
Speed	Constant at 70 km/h	Constant at 120 km/h
Engine speed	1250 rpm	2500 rpm
BMEP	5 bar	10 bar
BSFC	275 g/(kW h)	237 g/(kW h)
$P_{exhaust}$	1 bar	1 bar
$T_{exhaust}$	550 °C	790 °C
Exhaust gas flow	6.06E−03 kg/s	2.12E−02 kg/s

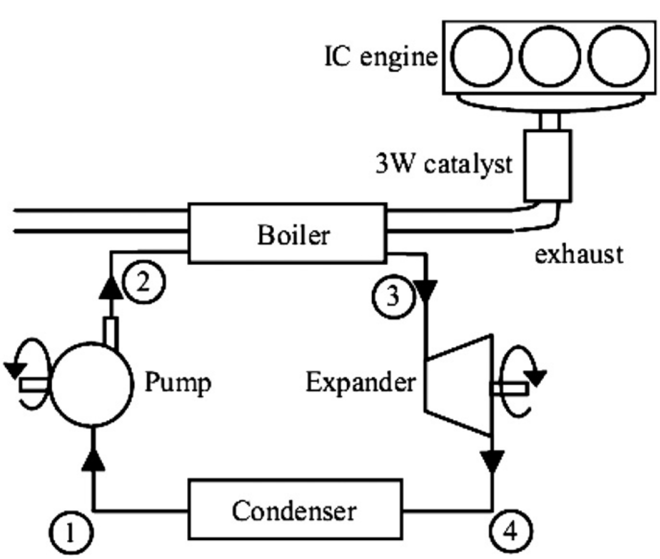

Fig. 8. Layout of the waste heat recovery Rankine bottoming cycle [53].

Table 4
Selective summary of *WHR* literatures using Rankine bottoming cycles.

Description of technique used in the study	Accomplishment	Reference
A specific thermodynamic analysis is examined to study the performance of a stationary internal combustion engine with an *ORC* system.	Achieved 12% increase in efficiency using Rankine cycles from exhaust gas and engine coolant. The latter only recorded a small fraction of overall improvement.	[51]
An *ORC* technique was used with high-efficiency, low emissions dual fuel low temperature combustion engine to examine the potential exhaust *WHR*.	7% of improvement of fuel economy was achieved. Average emissions of NO_x and CO_2 were also reduced by 18%.	[76]
Examined system concepts and control methods for exhaust *WHR* in hybrid vehicles through computer simulation.	Potential fuel economy efficiencies between 6–31% can be achieved. Dynamic system controls need to be investigated and developed.	[78]
Potential exergy from *WHR* of exhaust and coolant for 2.0 l Honda Stream *SI* engine that utilize *ORC* technique was studied. Changes were made on the engine to produce maximum waste heat energy.	Successfully showed an increase in thermal efficiency from 28.9% to 32.7% at a constant speed.	[77]
A study on WHR from dual-cycle system for power generation was presented. The system uses *TEG* and *ORC* technique to maximize *WHR*.	Shows an overall improvement mainly due to *ORC* that produces most of the energy improvement. Only small fraction of energy generated through *TEG* but may be useful for parasitic heat loss i.e., fans and power steering pumps.	[84]

4.5. Rankine bottoming cycle in the automotive industry

In recent years, interests in a Rankine bottoming cycle have prompted various automotive manufacturers to investigate its potentials. Many researchers [71–74] reported that Honda and BMW (Turbosteamer), respectively achieved a decrease in fuel consumption up to or more than 10% for their passenger cars. For commercial trucks, Nelson [75] reported that Cummins improves 10% of fuel consumption for their trucks by utilizing *ORC*. Many other research studies on Rankine bottoming cycles have been carried out which are discussed in Refs. [26,51,76–83].One notably exciting new research is the one proposed by Miller et al. [84] in which they explored the use of organic Rankine bottoming cycle integrated with *TEG*. A selective summary of various *WHR* literature using Rankine bottoming cycles is presented in Table 4.

5. Turbocharger

5.1. Introduction

A naturally aspirated (*NA*) internal combustion engine produces large amount of waste heat. The combustion process of fuel within the cylinder releases heat energy and exhausted through the exhaust manifold and finally to the environment. This wasted exhaust energy can be recovered using a turbocharger. Fundamentally, a turbocharger in its simplest definition is a type of supercharger that is driven by exhaust energy. The other type of automotive supercharger is the belt-driven supercharger. However, turbocharger will be the main focus of this subsection. A turbocharger is a type of gas turbine where heat and pressure in the expanding exhaust gas is used to increase engine power by

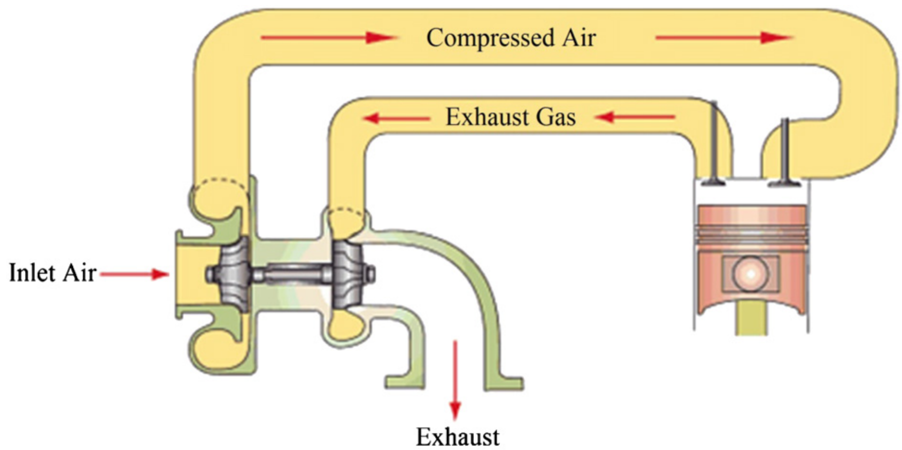

Fig. 9. Typical turbocharger with compressor wheel and turbine [85].

compressing the air that goes into the engine's combustion chambers. The turbine blades of the pump will be spun by the hot exhaust gases leaving the cylinders. A turbocharger component usually made up of (1) turbine, (2) shaft, (3) compressor, (4) waste gate valve, (5) actuator and (6) center housing and rotating assembly (*CHRA*). Fig. 9 shows a typical turbocharger.

Turbocharger technology make possible for engine downsizing through reducing pump work in SI engines. Also, its ability to increase power density greatly influences the revival of diesel engines into the industry in which most of diesel engines today are equipped with turbochargers. Turbocharging increases the air mass flow rate into the engine which significantly reduces particulates for diesel engines that are released into the atmosphere. Furthermore, it has been reported that turbocharged diesel engine can improve the fuel economy of passenger vehicles up to 30–50% and downsized turbocharged gasoline engine by 5–20% [86]. Turbocharging was largely adopted in diesel engines and recent motivation for more fuel efficient, economic and high-performance engines. Turbo charging has also slowly been established with gasoline engines although the demands are dissimilar to that of diesel engines.

5.2. Challenges of turbocharger

The earliest development of exhaust-driven turbocharger was recorded by Dr. Alfred J. Büchi in Switzerland between 1909 and 1912. In 1915, he proposed the first turbocharged diesel engine but gain no interests from the community [87]. In its early infancy, turbochargers were utilized mostly in heavy-duty applications. Traditionally, turbochargers had two important issues which are the main reasons for its low acceptance in the automotive industry. Turbochargers suffer turbo lag (i.e., hesitation or transient response) during low speed acceleration and there are major concerns with heated bearings. Turbo lag can poorly affect the drivability and performance of the engine.

Park et al. [88] studied the mechanism of a turbocharger response delay and stated that the interruption of boost pressure response is due to a combination of issues. The primary reason is due to the physical properties of the turbocharger systems i.e., weights of the turbine and compressor. The secondary reason (which is a resultant problem of primary factor) is mainly due to the reduced useful turbine energy occurred from disturbances in the operating mechanism. To improve the transient response, weights of turbine and compressor wheel can be reduced by using new materials. Additionally, reducing intake and exhaust system volume may also improve transient response of the turbocharger.

5.2.1. Variable geometry turbine—Reducing turbo lag

Variable Geometry Turbocharger (*VGT*) technology (also known as Variable Nozzle Turbocharger, *VNT*) is a type of turbine where the turbo controls the exhaust flow through the turbine blades by using variable vanes. At low engine speeds, the effective aspect ratio (A/R) is too large and the turbo will not be able to produce boost. Conversely, at high engine speeds, the A/R ratio is too small for the turbo which will choke the engine. As a result, increase in exhaust manifold pressures, high losses in pumps and eventually lower power output. A turbocharged engine equipped with *VGT* has small movable vanes to direct the incoming exhaust flow through the turbine blades. At different ranges of speed, the angle of the vanes would vary to optimize the flow of the exhaust gas.

There are various articles discussing *VGT*s. Shimizu et al. [89] examined the torque control of a small gasoline engine that was equipped with a *VNT* turbocharger. Authors reported torque improvement of about 27% at lower speed. Wang et al. [90] designed an electronic control for a *VNT* turbocharger which they demonstrated to have a good performance of pressure boost control under steady and transient conditions. Andersen et al. [91] investigated and benchmarked six closely matched turbocharged *SI* engines that are equipped with *VGT*s. They tested various engine operations and conditions including engine performance during low and high engine speeds, transient response and flow capacity. They concluded that more than 10% improvement were achieved during low and high engine speed torque for *VGT* turbochargers compared to fixed geometry turbochargers. Eichhorn et al. [92] explored the use of a turbocharger equipped with *VNT* to power auxiliary load i.e., the air conditioning system by using *WEDACS* (Waste Energy Driven Air Conditioning System). This system uses the turbine to produce mechanical energy and cold air. The mechanical energy is then converted into electrical energy by using an alternator while the cold air is used to cool the air conditioning fluid. The results show that from a 2 l engine, 50 W to 1.3 kW of power could potentially be recovered.

5.3. Recent developments of turbocharger

5.3.1. Two-stage turbocharger

An exciting development of turbocharger technology is the introduction of a revolutionary -stage turbocharger. Basically, a two-stage turbocharger has two different sized turbochargers assembled in serial configuration. The smaller sized turbocharger responds at lower speed by producing a higher torque that will reduce fuel consumption on the road [93]. Furthermore, the larger unit provides boost at higher engine speeds [93]. Based on the cluster of engines, different characteristic ranges of different

engines can be deduced. In the lower left-hand side of the figure, cost-effective engines or Base Engines utilized conventional technologies for example port fuel injection, one or none inlet cam phaser and simple mono-scroll turbines. In the lower right-hand side of the figure, Peak Power Engines group that have higher specific engine power range sacrifice low-end torque for high performance goals. Then, Peak Torque Engines group have achieved to increase their low-end torque at low specific power by using direct injection technology and one cam phaser. These *VTG* equipped Diesel engines can provide almost the same performance as the Peak Torque Engines thus revealing the potentials of gasoline engines for higher specific engine power.

From the conventional engines to one-stage turbocharging the specific low-end torque and specific engine power is limited to values of about 180 Nm/l at 85 kW/l up to 160 Nm/l at 100 kW/l. This limited power and torque ranges can be solved using the two-stage regulated turbocharging and up to 200 Nm/l of low-end torque can be delivered with power densities of more than 110 kW/l [94]. Due to the restrictions of single-stage turbocharging, the introduction of two-stage regulated turbocharging can significantly boost for higher charging pressure over the entire engine speed map. Furthermore, the respective stage loading of low-pressure stage and high-pressure stage can be reduced and efficiently distributed. In the two-stage turbocharger, there are two main components (or stages) that are designed to function very differently. The high-pressure turbocharger component is responsible for charging pressure at low engine speeds to ensure an increase of pressure during lower flow rate. It is situated upstream from the compressor side or downstream from the turbine side with respect to the main charging stage.

With the arrangement of the turbocharger, the low speed startup torque can be represented by the high-pressure stage to enhance the low-end torque of the engine. At higher power, low-pressure turbocharger with higher maximum flow rate can be utilized. The strategy in controlling the charging group is by using the turbine by pass; waste gate and compressor bypass control elements. The share of the required total turbine power for the turbocharger is determined by the turbine bypass which is generated by the high-pressure turbine. At low speed and full load, the turbine bypass is closed to allow for exhaust gases to pass both of the high-pressure and low-pressure turbochargers. Simultaneously, the air is compressed in two-stages at the compressor side. As the engine speed increases, the total pressure ratio also increases until finally the high-pressure turbocharger is fully deactivated by the opening of the turbine bypass on the exhaust side. During this point, the high pressure compressor is bypassed to reduce throttling losses. From medium speeds to high speeds, the high-pressure turbine is not required and only the low-pressure turbocharger is used to provide boost. To further reduce losses, below the naturally aspirated full load line; the waste gate is opened so that boost pressure is generated above the line only [94].

The BMEP of R2S system shows significant increase as compared to the conventional 1-stage turbo charging. Maximum BMEP level of 25 bar was achieved from the speed of 2000 RPM as compared to only about 21 bar for 1-stage turbocharger. The limit of 25 bar of BMEP was not due to the limitation of the turbocharger, but due to the engine. Concurrently, the specific power showed an increase from 85 kW/l to 100 kW/l starting from engine speed of 5000 RPM. There is also a reasonable increase in BSFC due to the increase of BMEP. The absolute intake manifold pressure also shows the advantageous of two-stage turbocharging system. The pressure increases from about 1600 mbar to the peak value of 2750 mbar at speeds from 1000 RPM to 1400 RPM. These data show that the two-stage turbocharger system can provide high low-end torque better than a single stage turbocharger.

Thus, the study can conclude that the advantages of a 2-stage turbocharger over a conventional 1-stage turbocharger are as follows:

- Total pressure ratios are higher than that of a 1-stage turbocharger. Higher power outputs are possible.
- Better efficiencies at low pressure (*LP*) stage.
- Produces better low-end torque.
- Dynamic performances are better with smaller High Pressure (HP) stage (low inertia).
- Minimizes the turbo lag.

Whereas the disadvantages of the 2-stage turbocharger includes more weight, bigger size, more required actuators and a boost pressure control more complex than 1-stage turbocharger.

5.3.2. *Turbocharging for a new type of engine*

Turbocharger technology has also been simulated in a new type of engine. Musu et al. [95] proposed a novel combustion concept called Homogenous Charge Progressive Combustion (*HCPC*) that permits reduction in soot and NO_x emissions in all operating conditions (during high and low engine loads). A formation of pre-compressed homogenous charge is progressively transferred into the cylinder to control the transfer flow rate and increasing pressures without relying on exhaust gas recirculation (*EGR*). This method is closely based on standard Homogenous Charge Compression Ignition (*HCCI*). The authors believe that this turbocharged concept permits engine speed to increase up to 6000 rpm, with indicated thermal efficiency of 45%, power density of 64 kW and 300 kPa of intake pressure.

6. Economical view and environmental impact

In the design and analysis of systems which are contributing with energy, economy is combined with technical improvements to achieve the highest outcome. Many researches [96] show methods with details to calculate economic factors in presence of efficiency improvement for industrial products and this paper is not going into details for it. However some researchers [97,98] have recommended that for considering the whole aspect of a technology improvement, the exergy analysis of the system should come into consideration too. The relation between sustainability of a process, exergy efficiency and environmental impact can be seen in Fig. 10. Sustainability and environmental impact have reverse relation which shows that when sustainability increases, environmental index will decrease.

For addressing sustainability issue and global environmental aspects the concept of exergy should come into consideration and sustainability index is a symbol to show the sustainability by

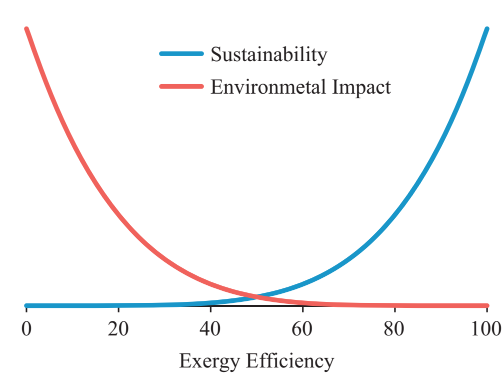

Fig. 10. Illustration of the relation between sustainability, environmental impact and exergy efficiency in a process [98].

numbers. It can be calculated from below Equation [98]:

$$Sin = 1/(1-\varphi) \quad (3)$$

This Equation clearly shows if the exergy efficiency increases from 0.8 to 0.9 is highly affect on the sustainability index compared to exergy efficiency increasing from 0.1 to 0.2 and finally can be seen that for generating a fix amount of power less pollutions of SO_2 and NO_x will produced which leads to less environmental impact clearly.

7. Conclusion

From the study, it has been identified that there are large potentials of energy savings through the use of waste heat recovery technologies. Waste heat recovery entails capturing and reusing the waste heat from internal combustion engine and using it for heating or generating mechanical or electrical work. It would also help to recognize the improvement in performance and emissions of the engine if these technologies were adopted by the automotive manufacturers. The study also identified the potentials of the technologies when incorporated with other devices to maximize potential energy efficiency of the vehicles. It should be noted that *TEG* technology can be incorporated with other technologies such as *PV*, turbocharger or even Rankine bottoming cycle technique to maximize energy efficiency, reduce fuel consumption and *GHG* emissions. Recovering engine waste heat can be achieved via numerous methods. The heat can either be "reused" within the same process or transferred to another thermal, electrical, or mechanical process. The common technologies used for waste heat recovery from engine include thermoelectrical devices, organic Rankine cycle or turbocharger system. By maximizing the potential energy of exhaust gases, engine efficiency and net power may be improved. Exergy efficiency is a concept which helps to obviously show the environmental impact by numbers. By increasing the exergy efficiency, sustainability index will increase and leads to less production of pollutants like NO_x and SO_2 during creating the same amount of power.

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